Broadband cross-layer networking in the home, over the hybrid Internet and over UAV aided mobile ad hoc wireless networks: Part B

Izhak Rubin

Professor

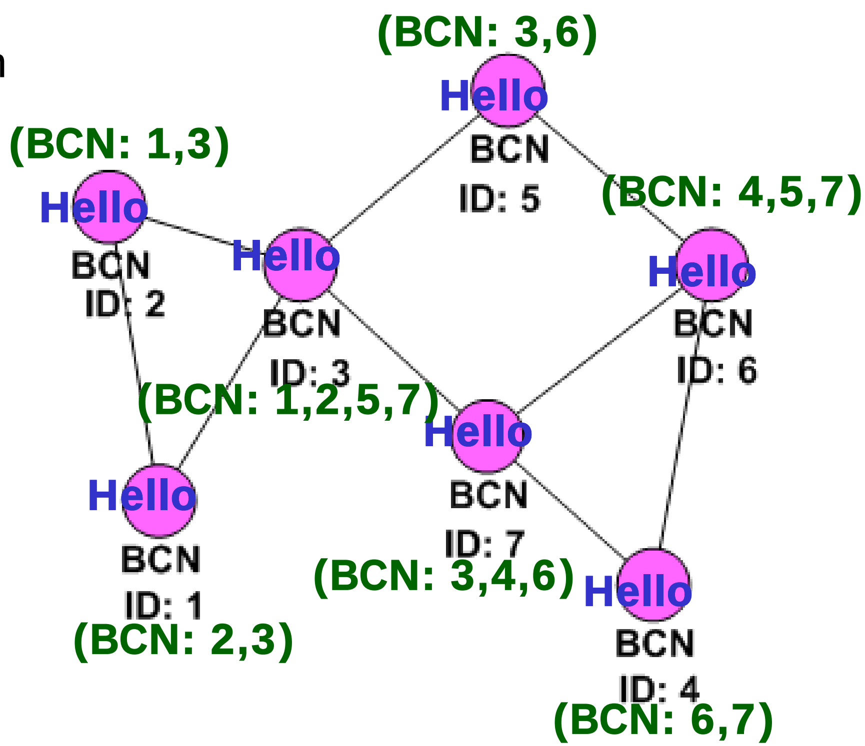
Electrical Engineering Department

UCLA

rubin@ee.ucla.edu

The Multi-Radio MBN Topology Synthesis Algorithm (MR-TSA)

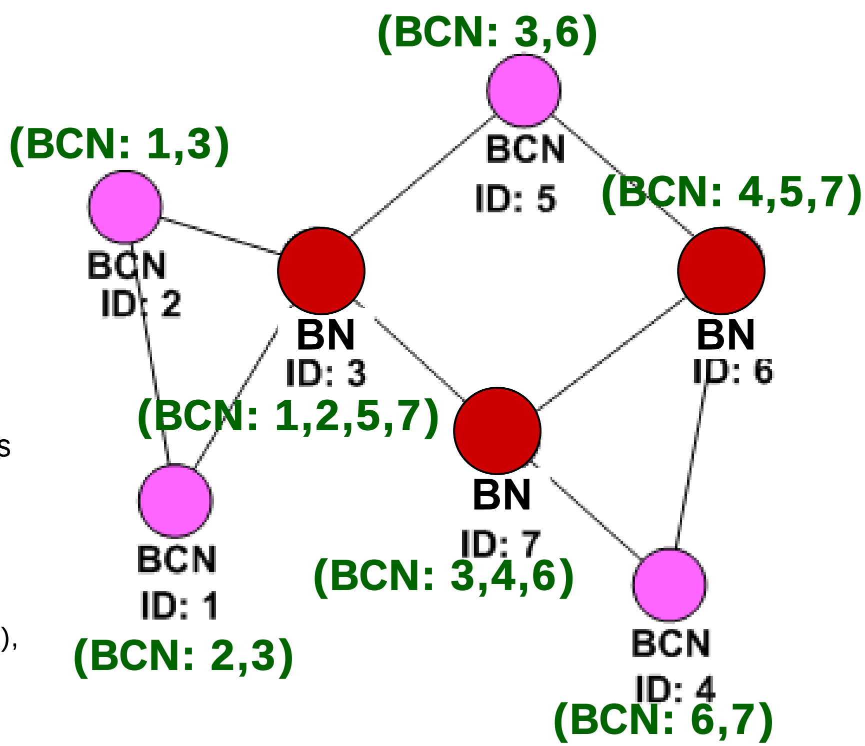
- Neighbor Discovery
  - Periodic Hello message exchange in both channels.
  - Each node learns its 1-hop neighbor information and 2-hop BN neighbor information in the high power channel.
  - Each node learns its 1-hop neighbor information in the low power channel.
- 1-hop association in the high power channel:
  - Every BCN attempts to associate with a BN neighbor with highest *Weight*.
- Multi-hop association in the low power channel:
  - Every BCN or RN attempts to associate with a BN through a multi-hop path.



Hello Message: ID, Status, Weight, BN Neighbor List

The Multi-Radio MBN Topology Synthesis Algorithm (MR-TSA)-Cont.

- BCN to BN Conversion Algorithm
  Any of the following condition is satisfied at a BCN *u*
  - **Client coverage condition:** BCN *u* has the highest weight among its BCN neighbors or BCN *u* has received at least one association request.
  - **2-hop BNet connectivity:** At least one pair of its BN neighbors do not connect to each other in ≤ 2 hops in the BNet.
  - **3-hop BNet connectivity:** At least one of its BN neighbors and one of its BCN neighbors do not connect to each other in ≤ 2 hops in the BNet.
- BN to BCN Conversion Algorithm
  All of the following conditions are satisfied at a BN *u*
  - **Client coverage condition:** Each one of BN *u*'s clients has more than one BN neighbor.
  - **2-hop BNet connectivity:** Any two of node *u*'s BN neighbors, e.g., BN node *v* and BN node *w*, either
    - (i) are directly connected to each other, and: node u has lowest highest weight among u, v, or w, or,
    - (ii) have at least one other common BN neighbor (e.g., BN x), and BN x has a higher weight than node *u* does.
  - **3-hop BNet connectivity:** Any one of node *u*'s BN neighbors (say, BN v) and any one of node u's BCN neighbors (say, BCN w) either
    - (i) are directly connected to each other, and: BN v has a higher weight than node u does, or,
    - (ii) have at least one other common BN neighbor (e.g., BN x), and: BN x has a higher weight than node *u* does.



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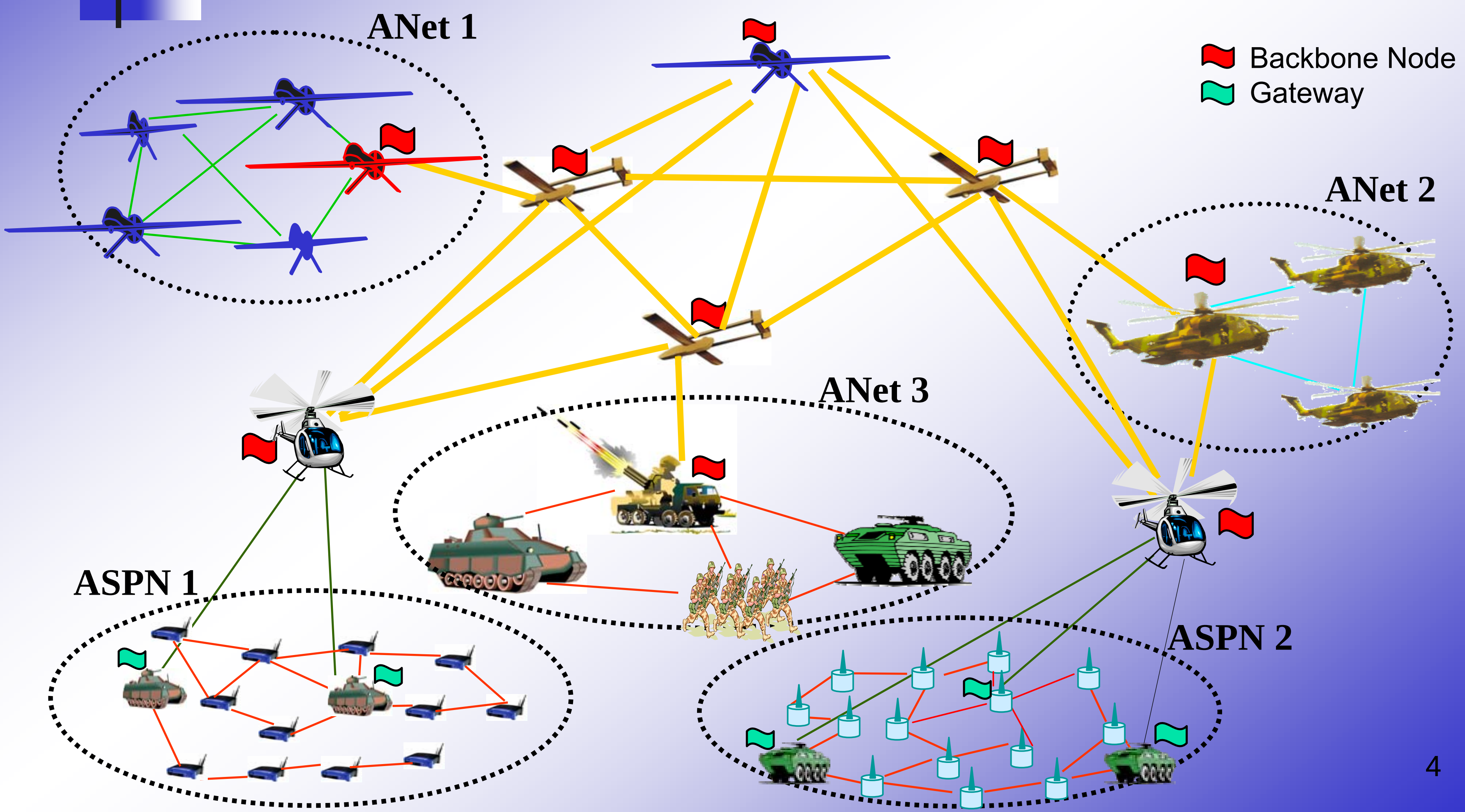
Hierarchical Configuration of UV-aided Mobile Backbone Network (UV-MBN)



Performance Features of MR-TSA

- Backbone Network Size:
  - MR-TSA guarantees to construct and maintain a connected backbone network whose size is independent of n (where n denotes the number of network nodes), only proportional to the area size.
- Algorithm Convergence Time:
  - MR-TSA convergences in constant $O(1)$ period of time (vs. n).
- Control Message Overhead:
  - It involves a control message size that is of the order (vs. n) of $O(1)$ per node.

Mobile Backbone Network Routing with Flow Control, Distance Awareness and Energy Saving

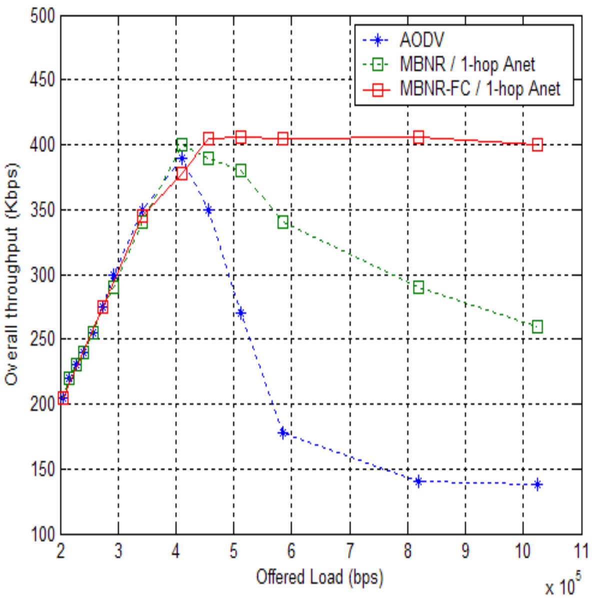
Hybrid Distance Awareness Routing Strategy

- Key Observations
  - When the number of BCNs is not able to form a backbone to cover the whole network area, backbone-only paths will limit the overall throughput capacity of the network.
  - Short-distance traffic obtains shorter path lengths by routing through all type of nodes, while long-distance traffic does not.
  - Long-distance traffic obtains routing overhead reduction by routing through backbone network, while short-distance traffic does not.
- Distance Awareness
  - Flows with path length $d \le d_{th}$ use non-backbone routing procedure.
    - RREQ messages are flooded among all types of nodes.
  - Flows with path length $d > d_{th}$ use backbone routing procedure.
    - Pure MBNR-FC operation
- MBNR-FC/DA procedure
  - New generated flows first go through the non-backbone routing procedure with a distance threshold d_{th}.
  - If non-backbone routing procedure fails to discover the destination, flows switch to backbone routing procedure.

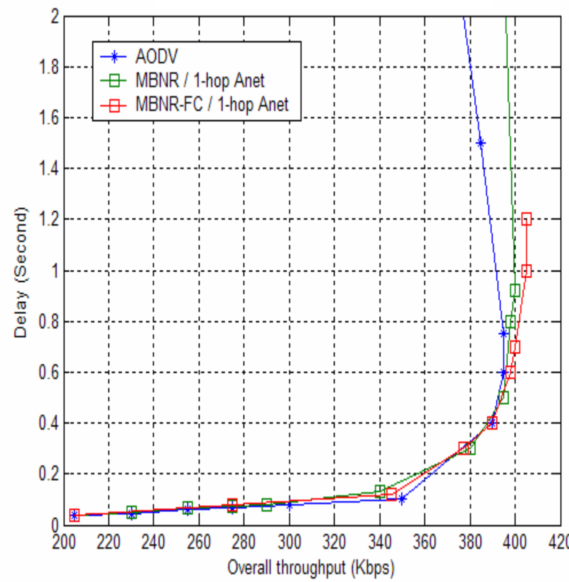
Throughput, Delay and Jitter Performance Features

- When the network is under heavy loading, the throughput, delay, delay jitter are much improved, due to the reduced flooding scope and the flow admission control mechanism.

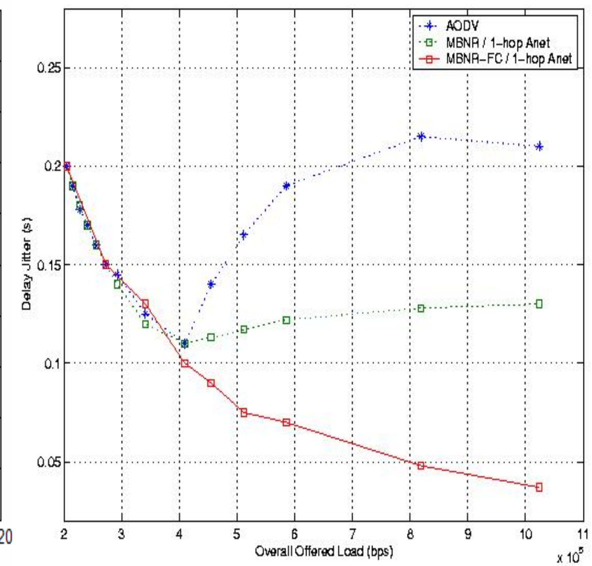
Throughput vs. Load



Throughput vs. Delay

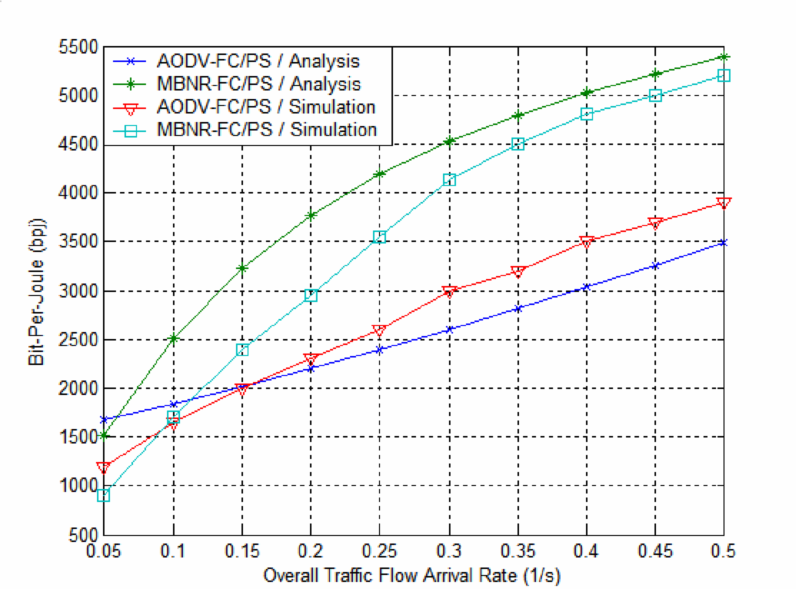


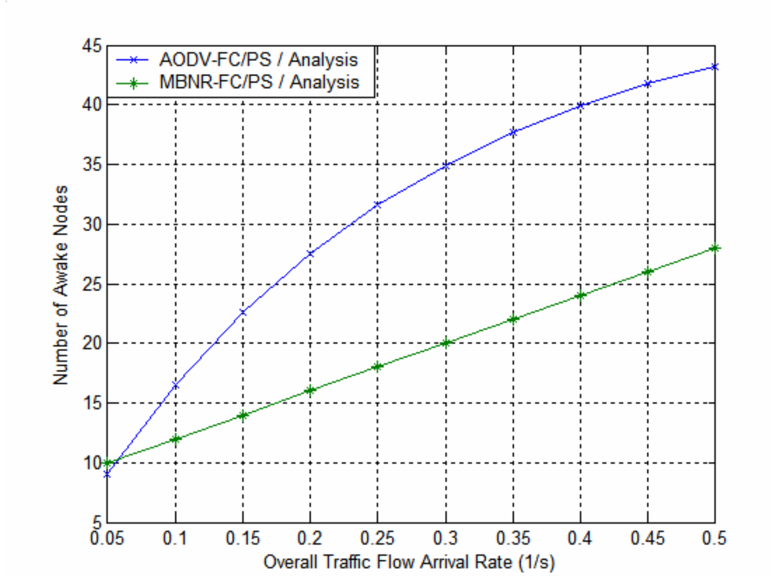
Jitter vs. Load



Throughput per Watt Performance under Complete Backbone Coverage

- When the number of active network flows is above a minimal level, the Throughput per Watt efficiency attained by the MBNR-FC/PS scheme is better than that achieved by a corresponding network that does not form a backbone structure (e.g., AODV-FC/PS).
- Flat ad hoc routing distributes traffic flows among all nodes, while the MBNR concentrates the traffic flow distribution. Thus flat ad hoc routing requires more nodes to be awake than MBNR does.





QoS Multicasting

Bnet Flooding Multicast Algorithm (BFMA)

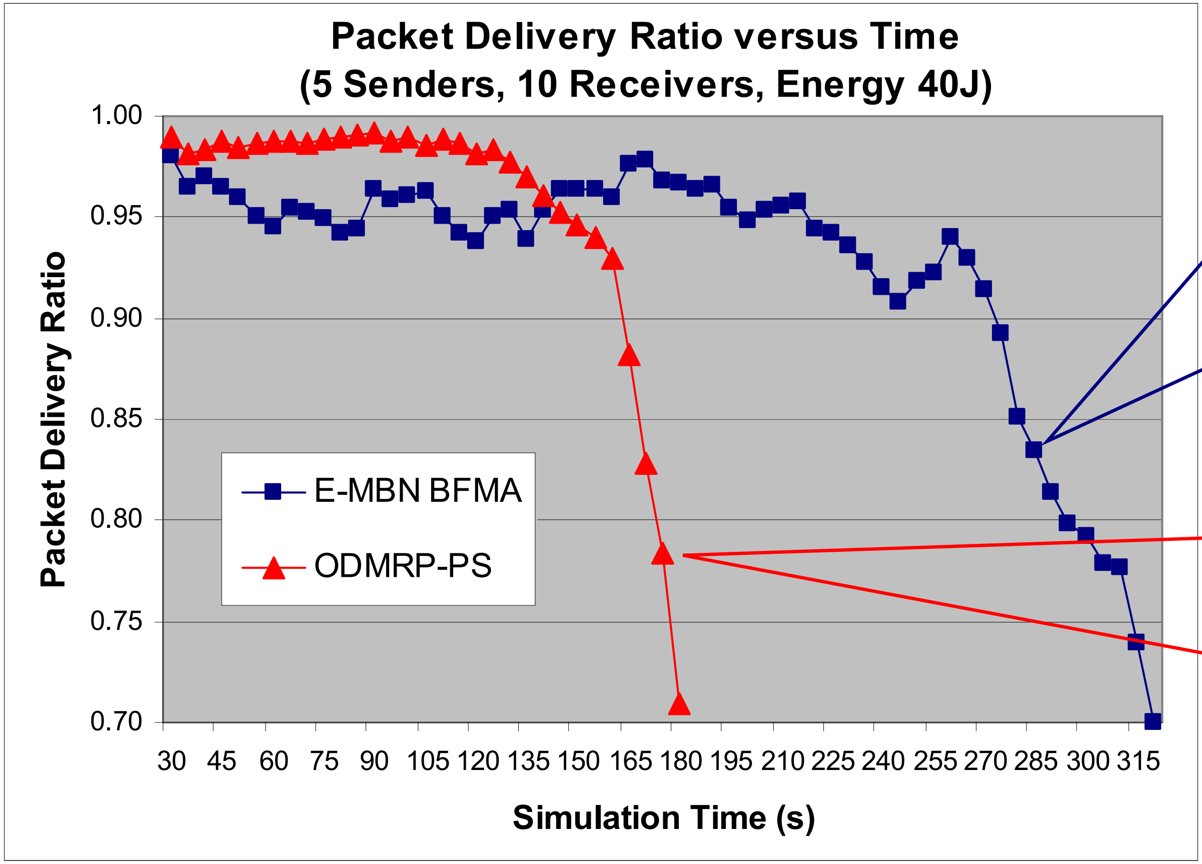
- Protocol Description:
  - The source BN floods each multicast message across the backbone network (Bnet).
  - All BNs participate in forwarding the multicast message.
    - Each BN will only forward a single copy of message.
  - Only BNs that have group clients copy the message for distribution to joined clients across their Anets.
- Features:
  - Highly robust under mobility induced topology changes.
    - The Bnet covers all clients and is structured as a mesh layout so that it exhibits higher connectivity features.
  - The selective flooding operation (using only BNs to forward messages) tends to yield excellent delay-throughput performance when the distribution scope is sufficiently high.
    - Please refer to our performance analyses and evaluations.

Energy-Aware MBN

Energy Conservation and

Network Lifetime Extension

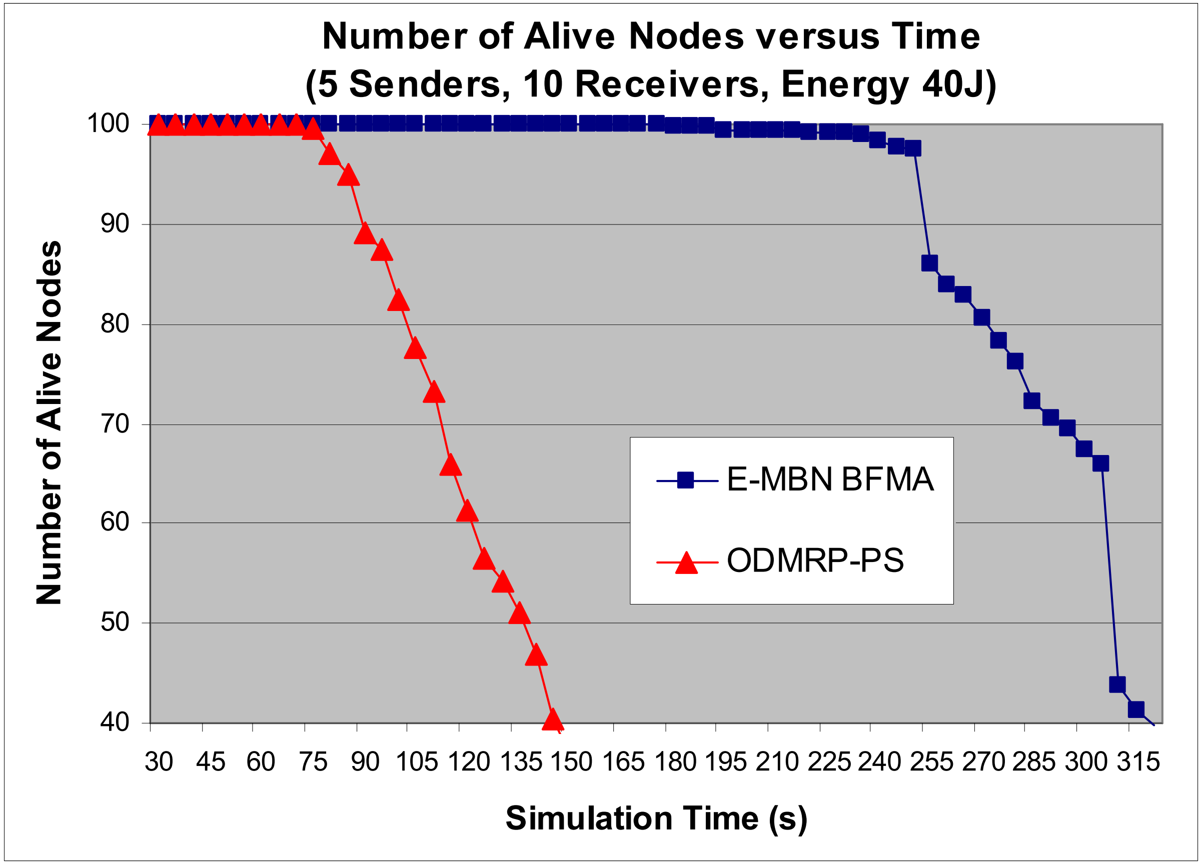
Packet Delivery Ratio vs. Time



With a PDR threshold of 70%, E-MBN based BFMA extends the lifetime of a network by approximately 70% beyond that of ODMRP-PS.

Although ODMRP-PS allows nodes to fall asleep to conserve energy, the algorithm does not have the mechanism to balance nodal energy dissipation.

Number of Alive Nodes vs. Time



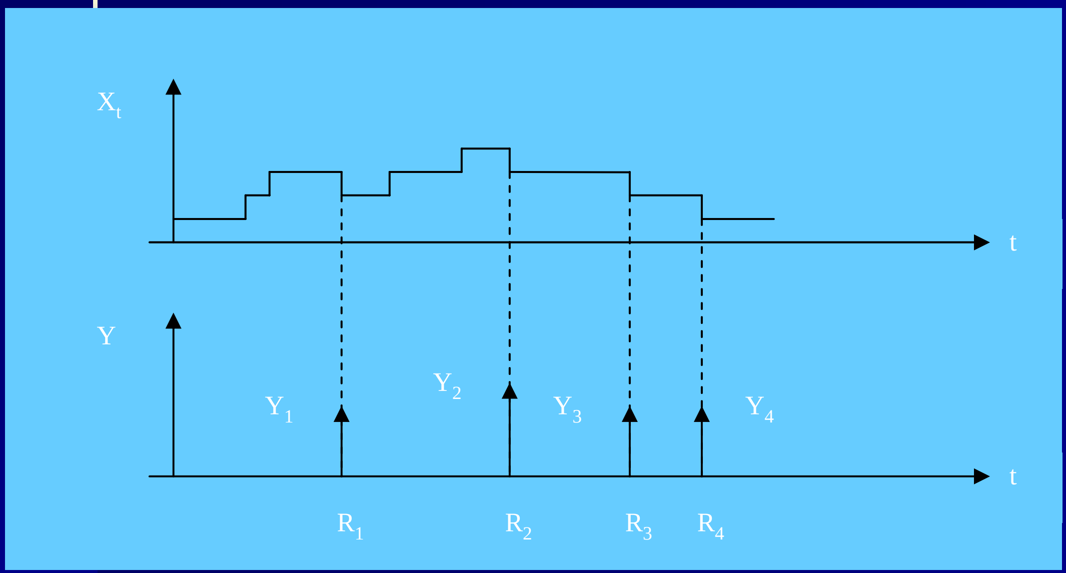
E-MBN based BFMA maintains a significantly higher number of alive nodes compared to ODMRP-PS. This is important since a higher number of alive nodes will achieve better area coverage in a sensor network. Moreover, in a dynamic scenario, nodes with energy could possibly move into an area to replace nodes that run out of energy, to maintain network connectivity.

Robust Flow Admission Control and Routing for Mobile Ad Hoc Networks

Robust Network Performance

- Robust Performance in literature:
  - Goodput: often used to measure the number of sequenced bits that a receiver receives per second.
    - Allows interruptions during transmission: this may not be desirable for realtime and other applications
- We introduce and study the following measures:
  - ***Robust Throughput***
  - ***Robust Throughput Capacity***

The Flow Size and Reward Processes



- The performance of the system is expressed in terms of the reward process $Y = \{Y_n\}$
- Let Y_n denote the payoff (or credit / reward) that the system obtains at the time of the n-th session/flow departure / reception.

$X = \{X(t)\}$ = Stochastic process representing the total number of sessions transported across the system.
$Y = \{Y_n\}$ = The associated reward process.

The n-th admitted and transported supported session is terminated at time R_n (and thus departing from the system), either due to interruption or due to its successful completion.

Lifetime of Links and Routes

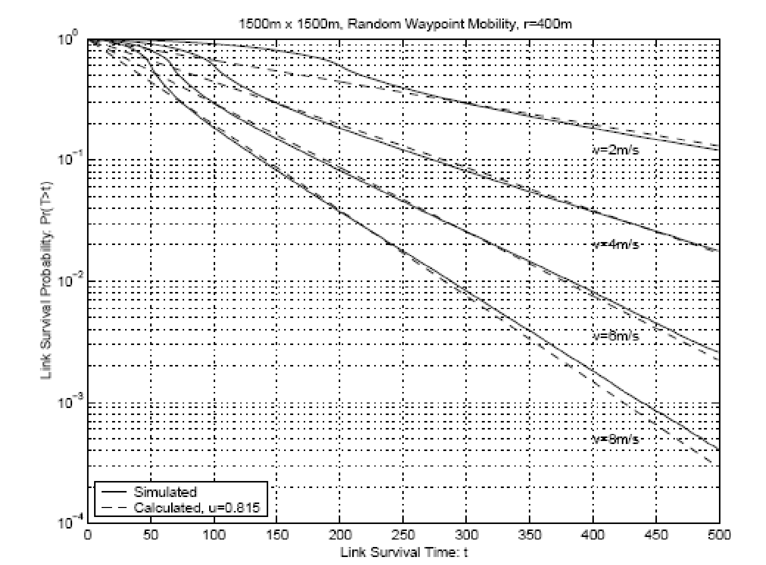
- Why calculate lifetime of links and routes?

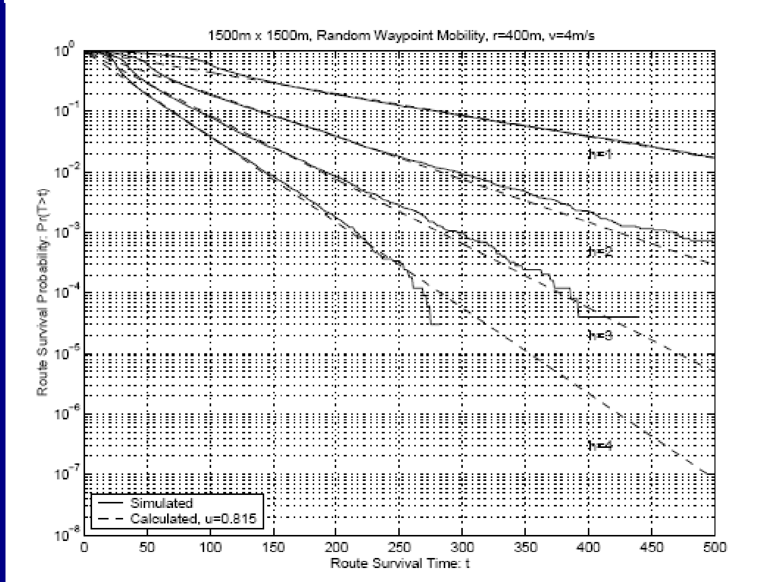
$$f_{r-CB} = \lambda_o(1 - P_B)E(F)E(T \mid S = 1)P(S = 1)$$

- Assuming a random waypoint mobility model (with low values assumed for the times spent by nodes in pausing at the area boundary), we have shown (with T_f = time to link fade) that the distributions of link and route survival times are well approximated by exponential distributions:

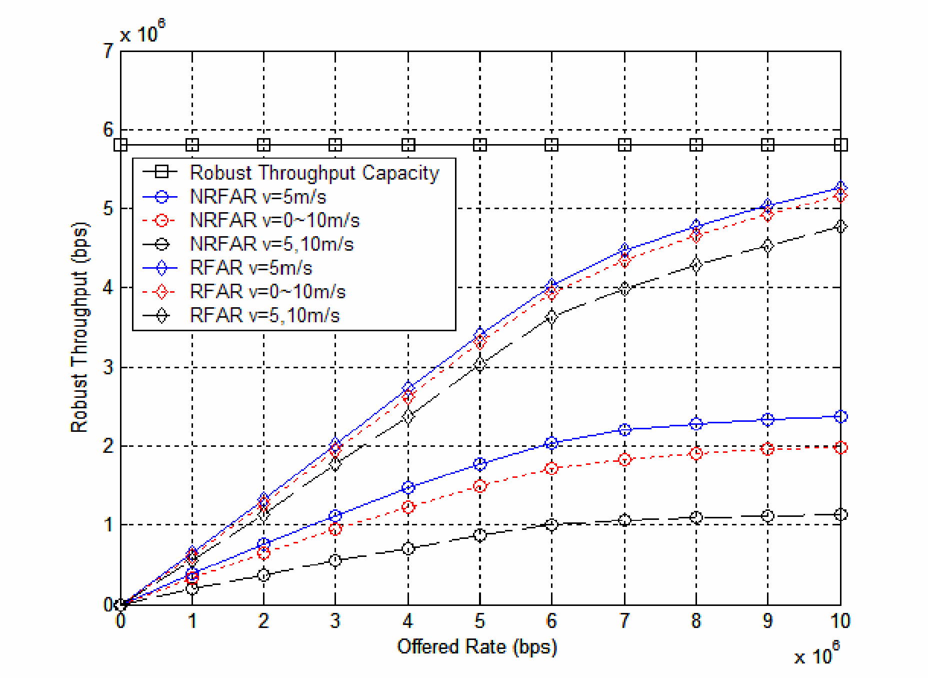
$$P(T_l > t) = e^{-(\frac{\mu(v_1+v_2)}{2r}+\frac{1}{T_f})t}$$

$$P(T_l > t) = e^{-(\frac{\mu(v_0+2v_1+2v_2+\ldots+2v_{\pi-1}+v_\pi)}{2r}+\frac{\pi}{T_f})t}$$





Robust Throughput Performance



In the figure, we exhibit the robust throughput behavior of the network system under the use of the RFAR and NRFAR algorithms. We observe that as the offered loading rate is increased to a high level, the robust throughput level attained by the RFAR algorithm approaches the system's robust throughput capacity level, while that achieved by the NRFAR scheme is equal to only about 40% of the (RFAR) robust throughput capacity level. The robust throughput performance behavior is noted to degrade as the nodal speed levels are increased. This degradation is more pronounced for the operation conduced under the NRFAR scheme.

Note: when node's speed = 5m/s = const., the Robustness index of a path is proportional to its hop length.

Cross Layer Physical, MAC and Routing for Mobile Ad Hoc Wireless Networks

Power Control Spatial Reuse MAC Schemes and Cross Layer Operations

Cross-Layer Joint Power Control–Scheduling Problem in Wireless Access Nets

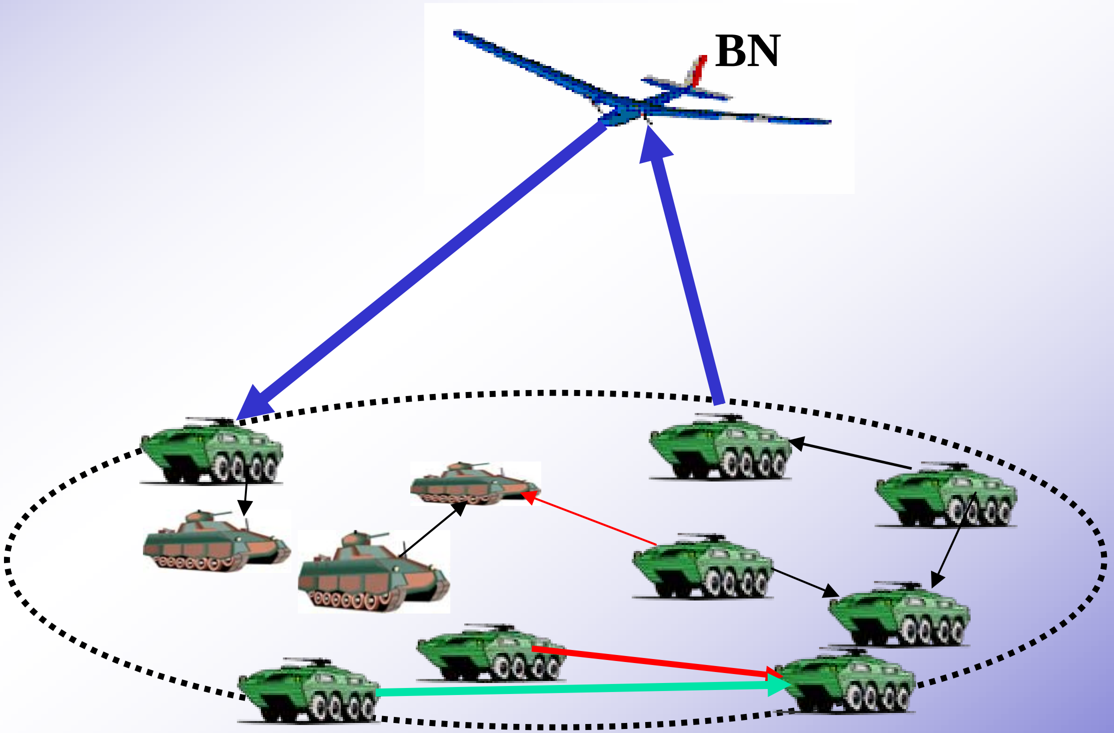


Illustration of an access net (ANet), including a backbone node (BN) and 11 regular nodes (RNs)

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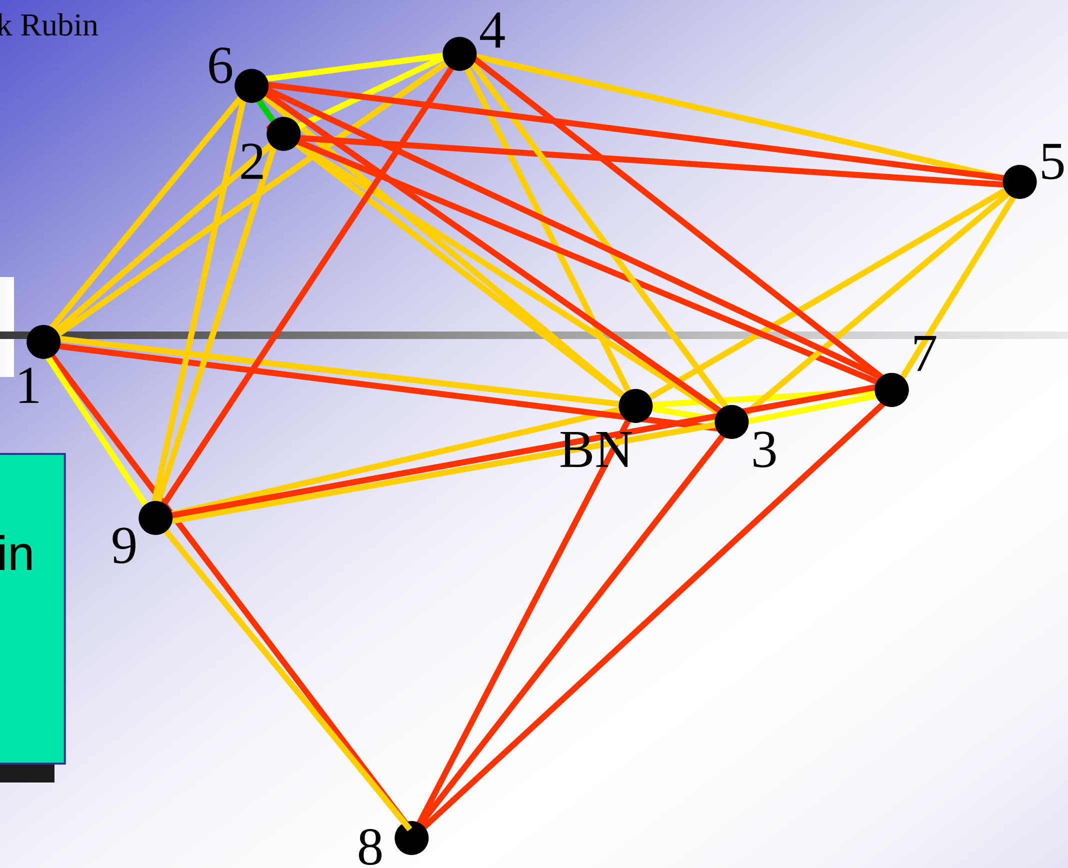
Power Control Spatial-Reuse MAC DA/TDMA



large increase in spatial reuse factor

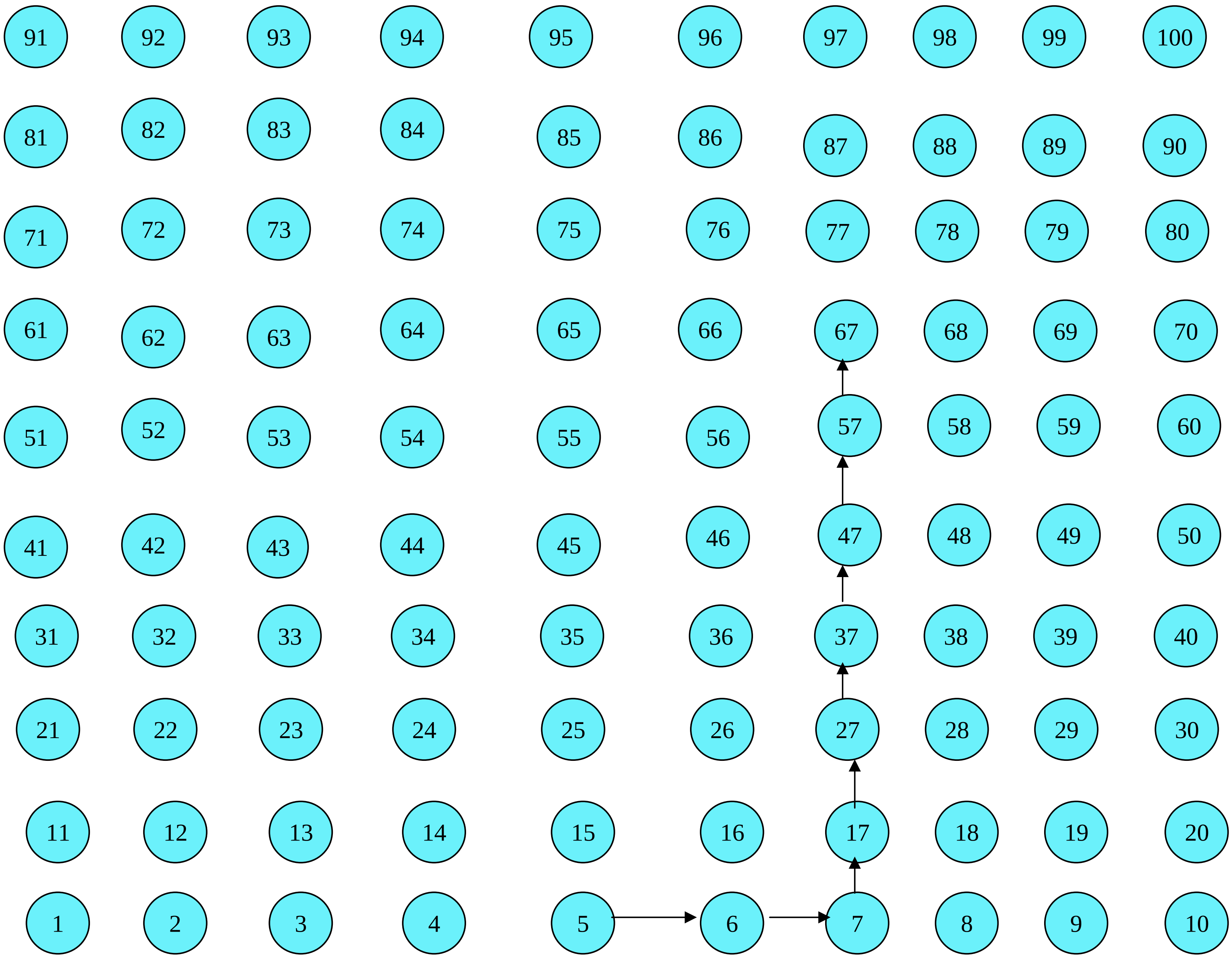
Power: 1mW
Power: 10mW
Power: 50mW
Power: 100mW

Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10
BN → 3 10mW	8 → 9 50mW	1 → 4 50mW	BN → 7 10mW	9 → 1 10mW	9 → 2 50mW	5 → 3 50mW	BN → 3 10mW	BN → 7 10mW	2 → 1 50mW
4 → 2 10mW	6 → 4 10mW	BN → 3 10mW	1 → 9 10mW	2 → 6 1mW	8 → 7 100mW	6 → 1 50mW	6 → 9 50mW	9 → 8 50mW	7 → 5 50mW
9 → 1 10mW	BN → 7 10mW		2 → 4 10mW	3 → 5 50mW				4 → 5 50mW	

Cross –Layer Adaptations

Cross Layer Operation involving the PHY, MAC and Network Layers

- The adaptive MAC schemes noted above is further extended to include cross layer operations that make adjustments at the routing level.
- Consequently, we develop integrated physical, MAC, link and network layer routing protocols and algorithms.
- We extend the cross layer mechanisms to allow the networking module to jointly select and adjust the MCS, MAC scheduling process and the underlying flow’s route.
- Such a scheme engages in the setting of an active’s node’s radio to use a selected MCS, to operate at a computed data rate, to specify the identity of its hop neighbor(s) to which it aims to forward each flow’s packets (by setting the latter to reside at selected distance range(s) and thus impacting the selection of the route for its underlying active flow) and to jointly adjust the involved MAC scheduling operation.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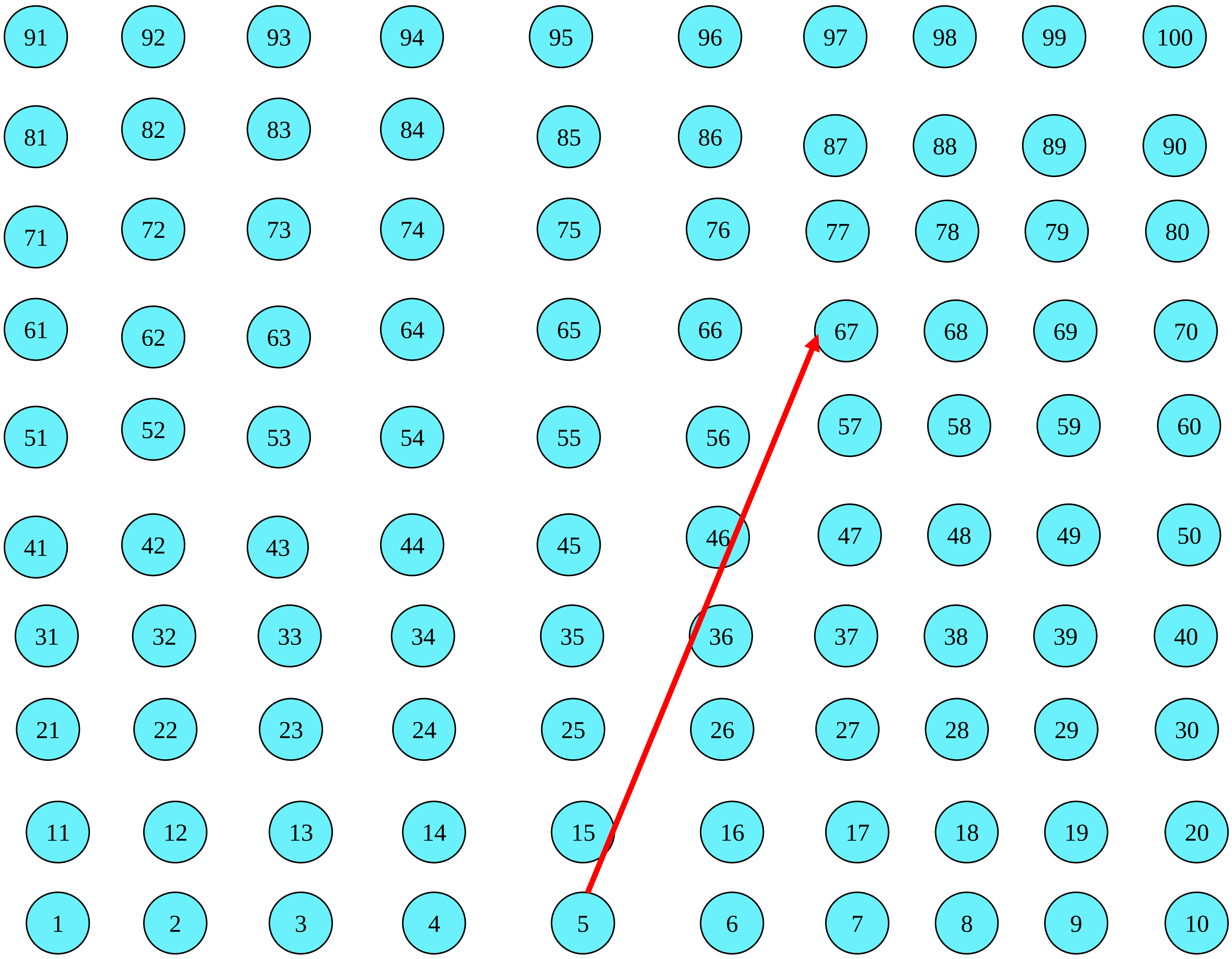
1 2 3 4 5 6 7 8 9 10



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1- Forwarding Range Selection

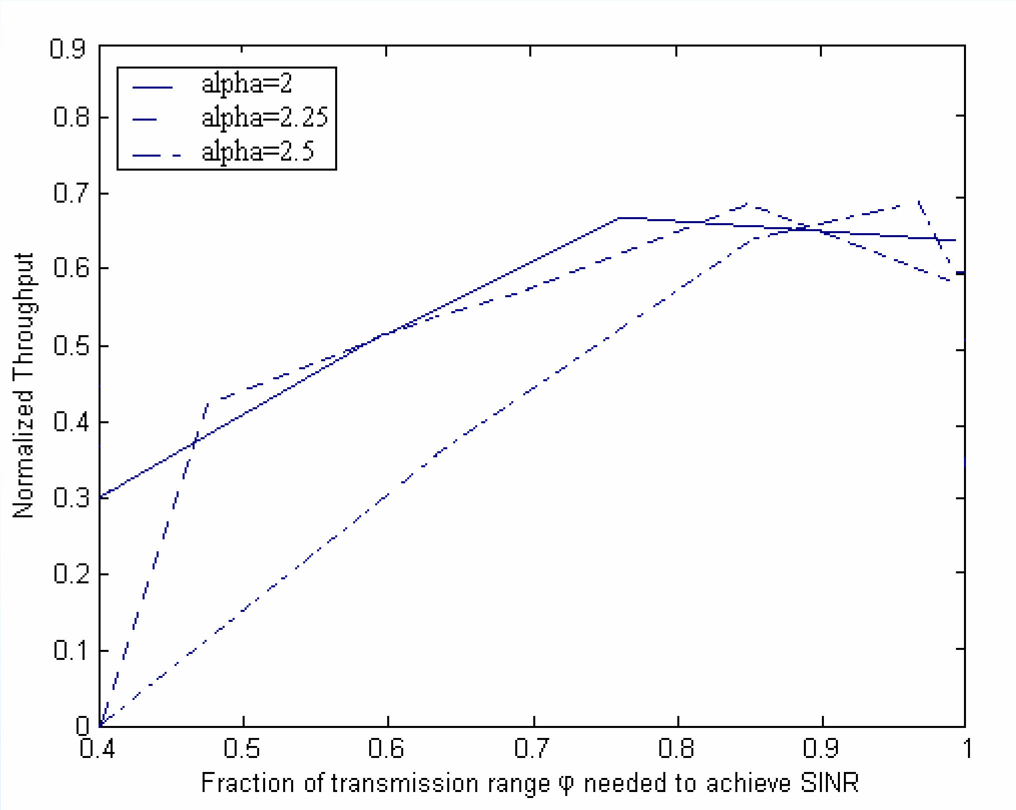
Fixed Parameters:

- Transmit power level
- Data rate

Varied Parameters:

- Forwarding to transmission range ratio φ

Case#3: Multihop Network



125 node multihop network, over a 400m x 400m area of operations, where nodes operate at a transmit power level of 10 dBm and a data rate of 2 Mbps.

The offered load to the network is 1.6 Mbps.

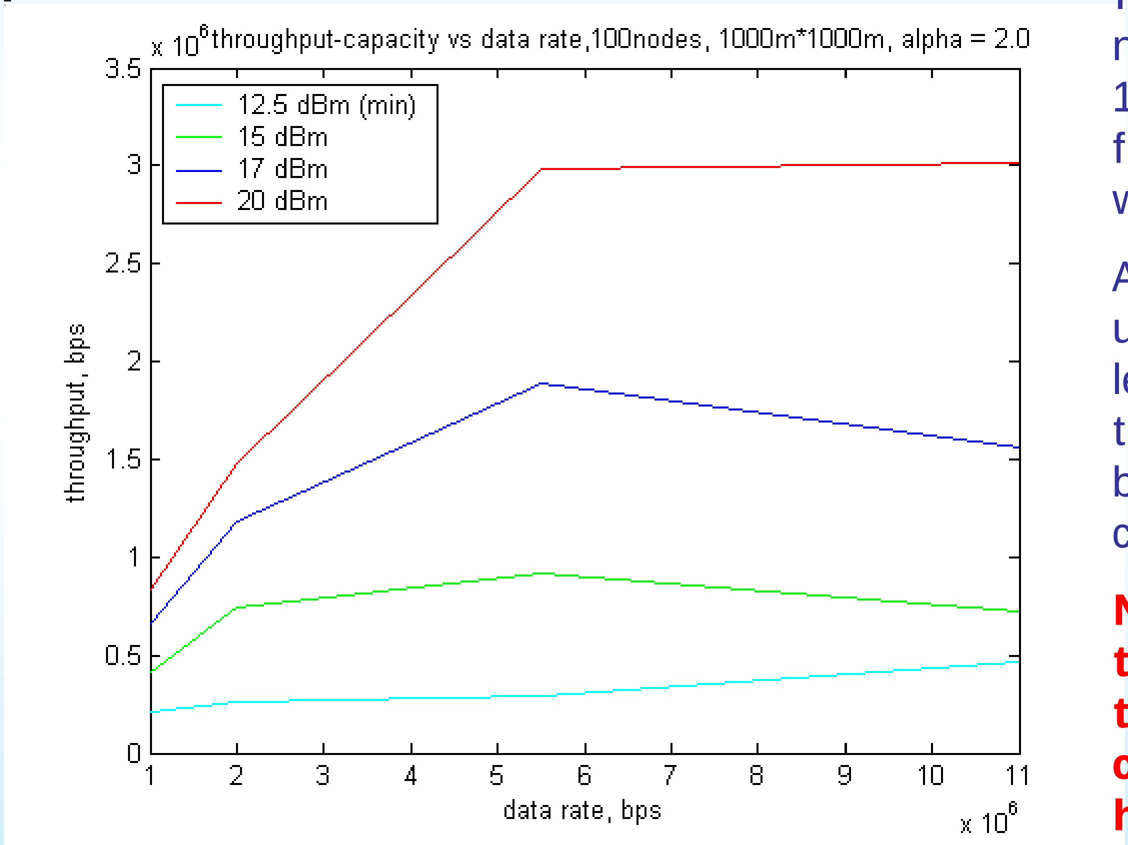
The SINR threshold used corresponds to a BER = $3*10^{-4}$ (using DQPSK modulation)

In a multihop network, using the highest possible forwarding range may not be beneficial for the throughput of the network.

2- Transmit Power and Data Rate Selection

- Fix the forwarding range/ transmission range ratio φ
- Vary the transmit power level and data rate combination that best enhance the delay-throughput performance of the network.
- We use typical transmit power level and data rate parameters found in commercially available IEEE 802.11 cards

Case #2: A Multihop Network, Free Space Propagation, α=2

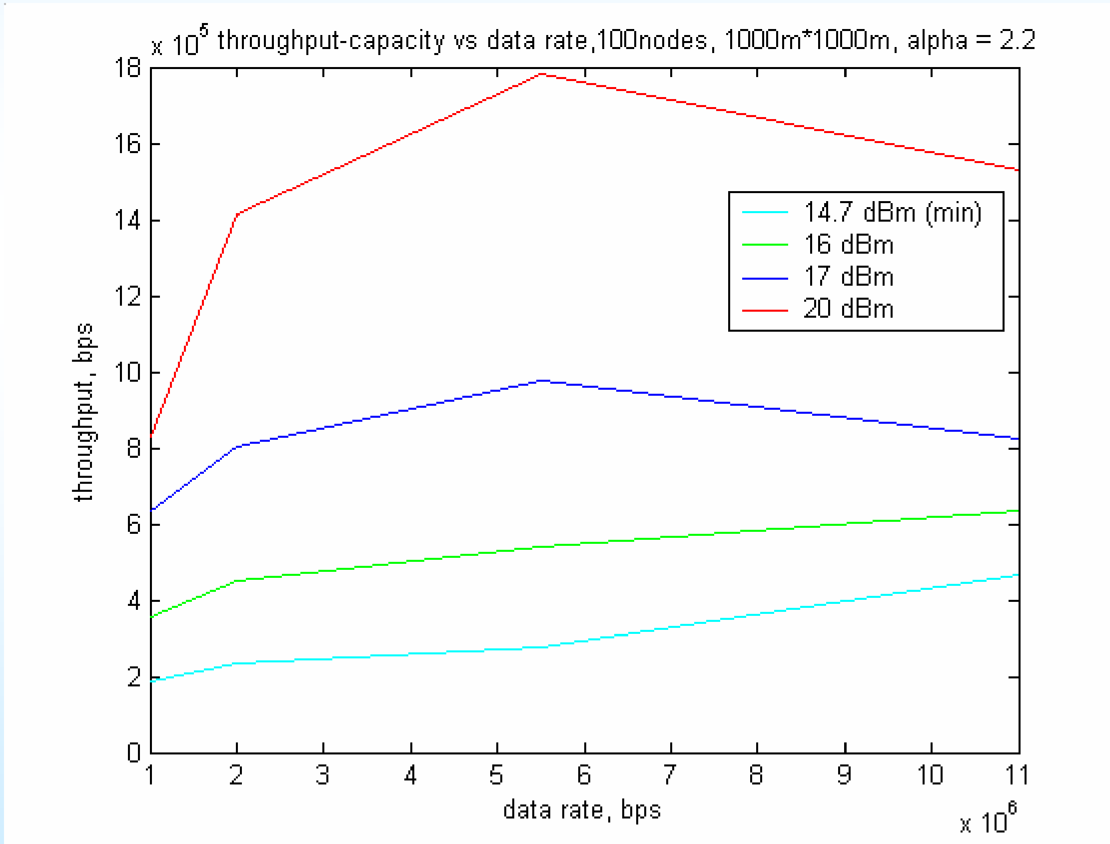


In this case, we simulate a network of 100 nodes in a 1000m*1000m terrain using a free space propagation model with α=2.

As can be seen from the figure, using the highest transmit power level and the highest transmission data rate proves to be the most beneficial in this case.

Note the inefficiency of using the lowest transmit power that keeps the network connected (cyan) due to the high path length and the drop in throughput due to hidden nodes.

Another multi-hop network, free space propagation, α=2.2



We carry out this simulation using the same topology of 100 nodes uniformly distributed over a 1000m*1000m terrain. We see in this case that the maximum throughput is attained using the maximum transmit power but using the 5.5 Mbps transmission rate.

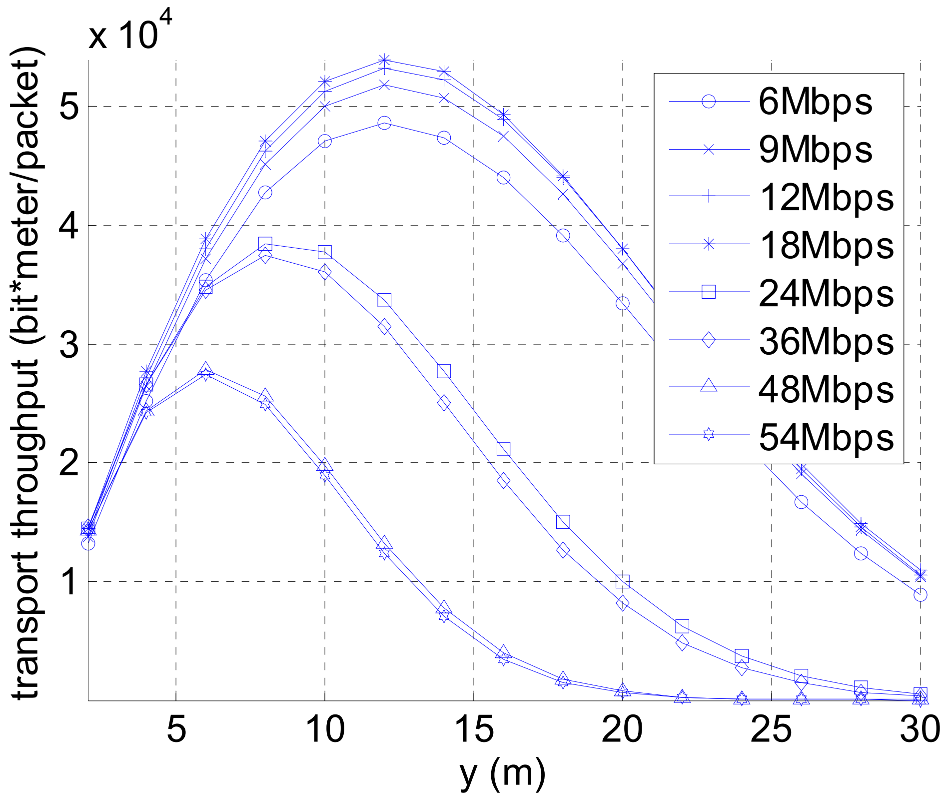
This can be explained that, under this propagation model, the increase in SRF introduced by using the 11Mbps data rate does not compensate for the resulting increase in path length and also does not compensate for the decrease in throughput due to hidden nodes.

Distributed QoS based Cross-Layer Operations: routing and rate control protocols and algorithms in wireless multi-hop networks

- Datagram Based
- Flow based

Nodal Transport Throughput Behavior: Sensitivity to Selected Forwarding Range

Datagram based cross-layer operation



Note:

a. Under these conditions, it is best to set rate to 18 Mbps

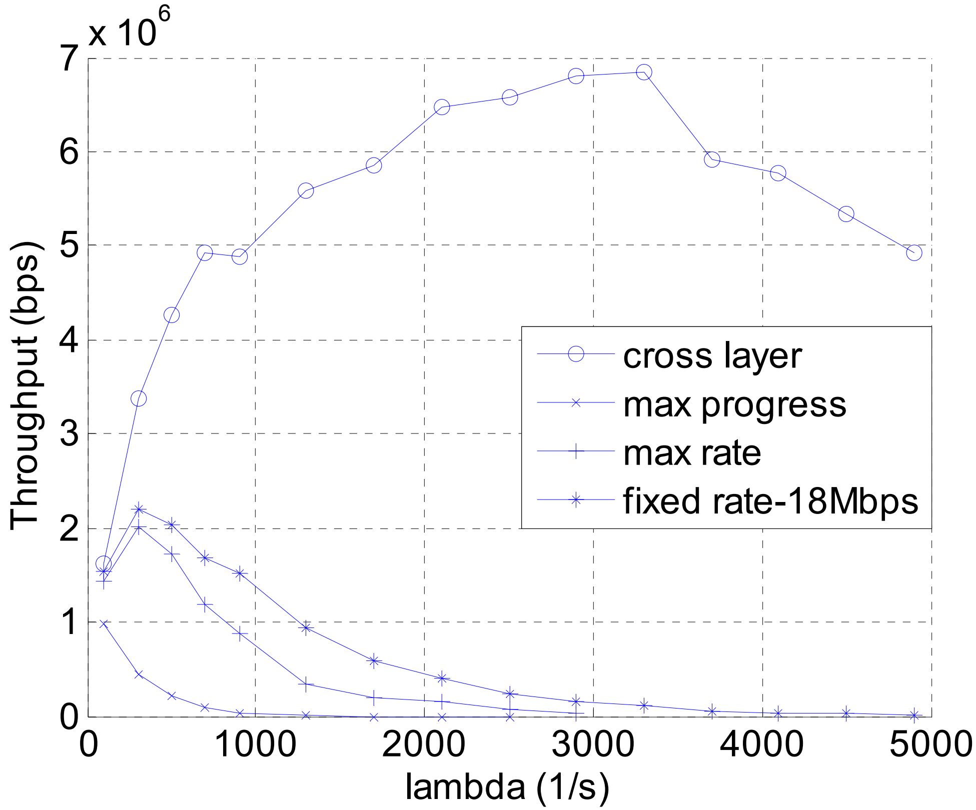
b. Sensitivity to forwarding range is observed

Figure 3. Expected packet transport S°t,0 vs. hop forwarding range y levels, using the PHY data rates provided by 802.11a PHY schemes.

Distributed QoS-driven cross-layer routing and rate control algorithm

- Goal
  - A distributed mechanism that is used by each relaying station to perform joint rate and routing adaptations in the multi-hop random access network system, on a packet-by-packet base
- Consider a network carrying multiple connectionless datagram type end-to-end data packet flows
- Packets may desire a certain QoS objective: each packet is subjected to targeted (flow based) end-to-end throughput and delay performance requirements
- Each station monitors (on a sliding window basis) its activity and network activity states, and uses these data to adapt the selection of its parameter vectors
- The mechanism strives to ensure that flow throughput and end-to-end packet delay target levels are met. Once satisfied, the algorithm selects parameters that serve to enhance the transport throughput level, thus selecting a QoS based cross layer parameter set that tends to not over-capture network wide resources.

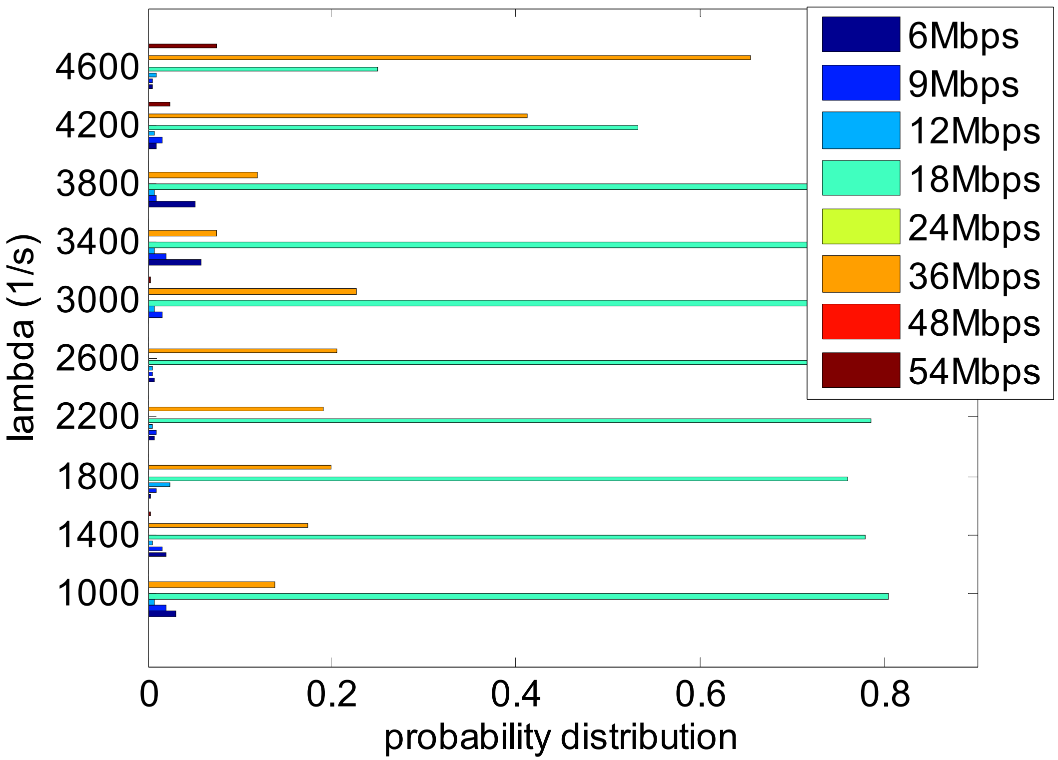
Performance evaluations



Throughput performance versus medium access rate λ.

- The proposed cross layer joint routing and rate-control algorithm outperforms the other algorithms
- Note the superior throughput performance attained by using the cross layer scheme under highly congested scenarios
- The performance gains are enabled by the capability of the cross layer algorithm to dynamically adapt to underlying monitored network loading and interference conditions.
- The cross-layer algorithm presented above provides also for a QoS based operation.

Performance evaluations - 2



Transmission rate selection histogram of the distributed adaptive algorithm.

- The data rate selection distribution histogram realized by the proposed cross-layer algorithm is plotted, under several selected loading levels
- The figure confirms the ability of the scheme to effectively adapt to varying levels of medium access activity
- As the system activity is monitored to indicate a higher congested network state, a higher transmit rate level is typically automatically selected by the cross layer scheme

Professor Izhak Rubin

Network Management for Multi Segment Hybrid Networks

High Utility Network Management for Multi Segment Multimedia Networks

- Multiple segments are employed; e,g.,
  - OFDM bands
  - Terrestrial and multi orbit space based platforms
  - Multi hierarchy wireless / wireline access and backbone networks
  - Diversity of users, applications and QoS requirements
- Cognitive radios and other adaptive mechanisms are jointly employed to discover the spatial – temporal availability of communications, relay, storage and processing resources
- Our network management structure proceeds to rapidly establish explicit routes across the hybrid wireless-wireline, access – backbone, private – public Internet and communications transmissions and networking resources allocated to flow classes to ensure the attainment of highest utility.

High Utility Network Management for Multi Segment Multimedia Networks

- Our management schemes ensure QoS performance to admitted flows: Low complexity algorithms configure in realtime the allocation of resources to (aggregate) flow classes and optimize the split distributions of flows across the multiple available segments.
- Cross layer and energy-aware operations.
- Performance utility metrics include factors such as: security, robustness, delay, robust-throughput, discard ratio
- Rapid re-configuration and re-constitution upon failures, mobility, portability and degradations.

Utility Measure

The utility measure for class m traffic when flow vector x_m is used, and flow rate x_{mn} is directed across segment / route n, is given by:

$$U_m(\mathbf{x}_m)=\sum_{n=1}^{R_m} U_{mn}(x_{mn})$$

Special cases:

$$U_m(\mathbf{x}_m)=\sum_{n=1}^{R_m} x_{mn}/w_{mn};$$

$$U_m(\mathbf{x}_m)=\sum_{n=1}^{R_m} x_{mn}/w_m = f_m/w_m.$$

The optimal joint flow admission control and routing matrix X is obtained to yield:

Optimal U = optimal Max_Min_Fair $\{U_m(\mathbf{x}_m), m=1,2,...,M\}$.

The Joint Flow admission and Routing Optimization problem

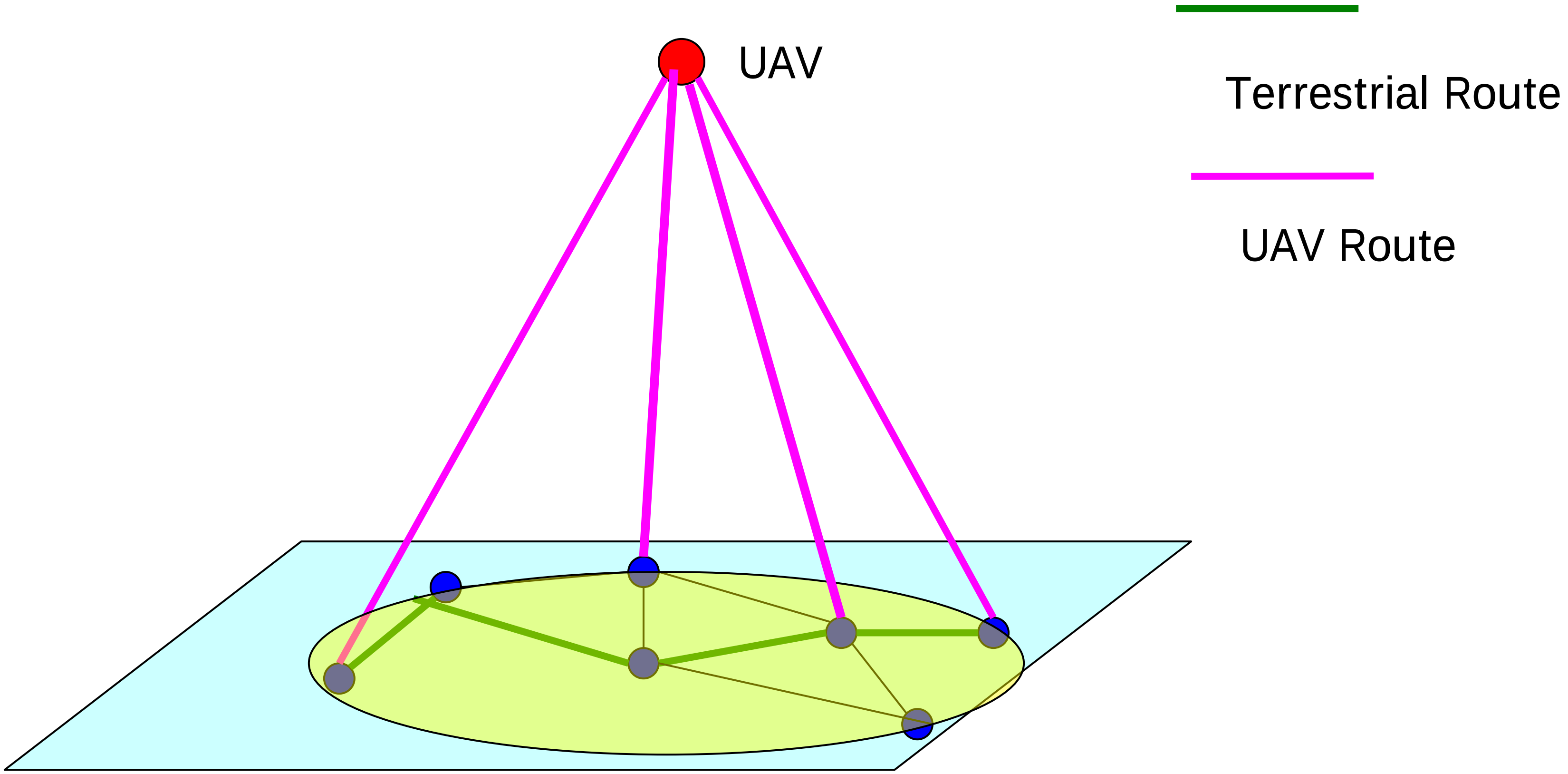
- Optimization problem
  - Objective function
  - Minimum rate constraint
  - Maximum rate constraint
  - Multiple Segment
  - Dynamic discovery of resources
  - Dynamic fluctuations in traffic and service demands
  - Realtime control

Optimal Algorithms

- The algorithm proceeds in an iterative manner to find the optimal data rate to be allocated for each of the flows across each candidate route.
- In each iteration, the algorithm solves Linear / Convex Programming problems aiming to monotonically increase the data rates of certain flows (identified as ‘active flows’), stopping when certain bounds are reached (thus becomes ‘completed flows’).

Placement of UAVs as Communication Relays Aiding Mobile Ad Hoc Wireless Networks

Network Model Illustration



Optimal Algorithm: Heuristic Schemes

- To reduce the complexity of the computation, we have been developing numerically efficient heuristic algorithms
- The split of flows among the two (terrestrial and UAV) segments is performed through the use of a heuristic criterion, thus yielding a suboptimal solution. In this manner, the use of the linear programs is avoided.

Illustrative System Configuration

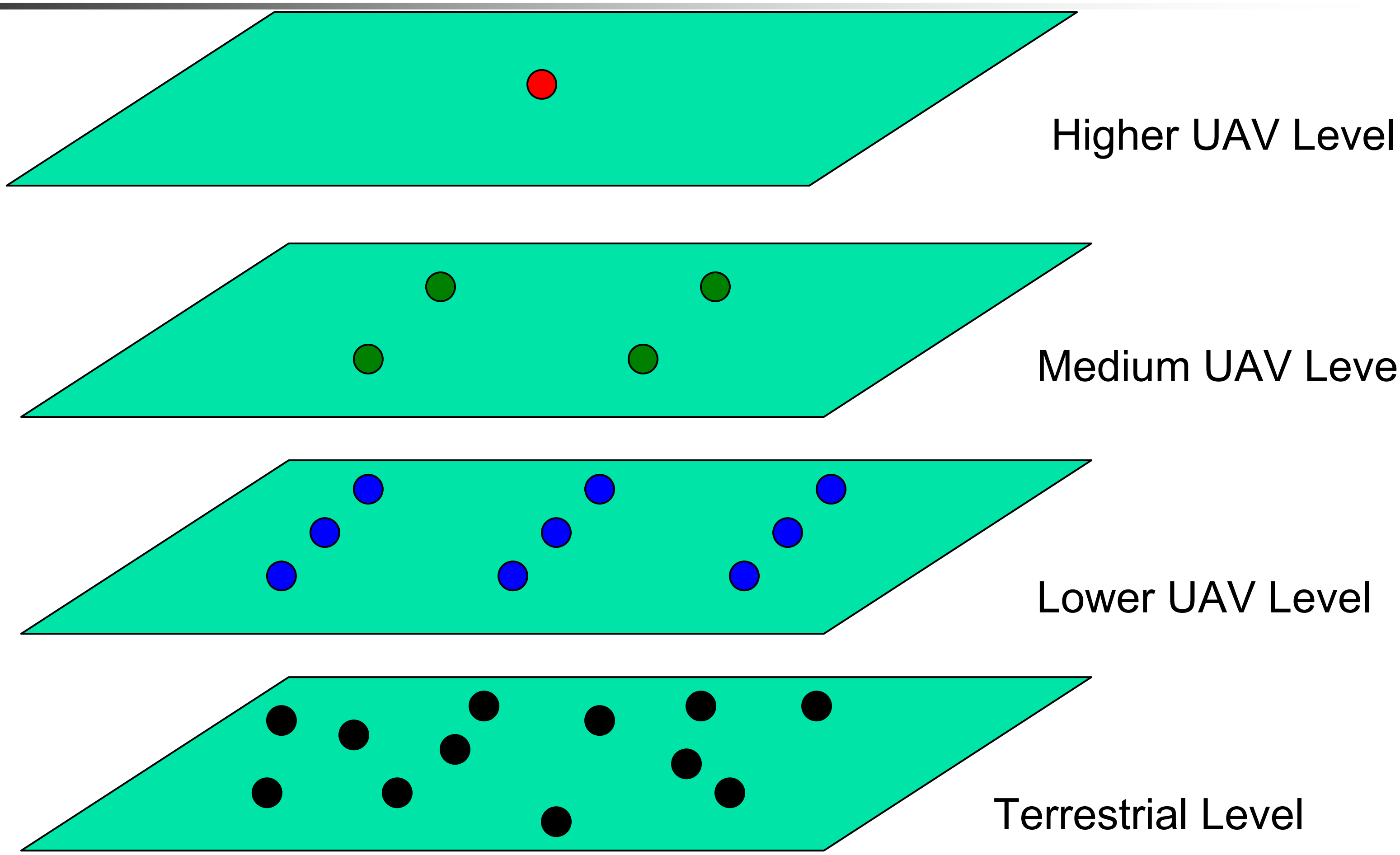
- 25 nodes in the system; 30 traffic classes are generated; 1 UAV

TABLE I

UAV POSITIONS, THEIR FOOTPRINT AND CAPACITY

ID	X,Y	Z(m)	FP $10^3 m^2$	covered nodes	capacity (Mbps)
1	center	4000	64	25	50
2-5	4 locations	3000	36	16	200
6-14	9 locations	2000	16	9	400

Illustrative System Configuration: Candidate Locations of a UAV Platform



Performance Illustration

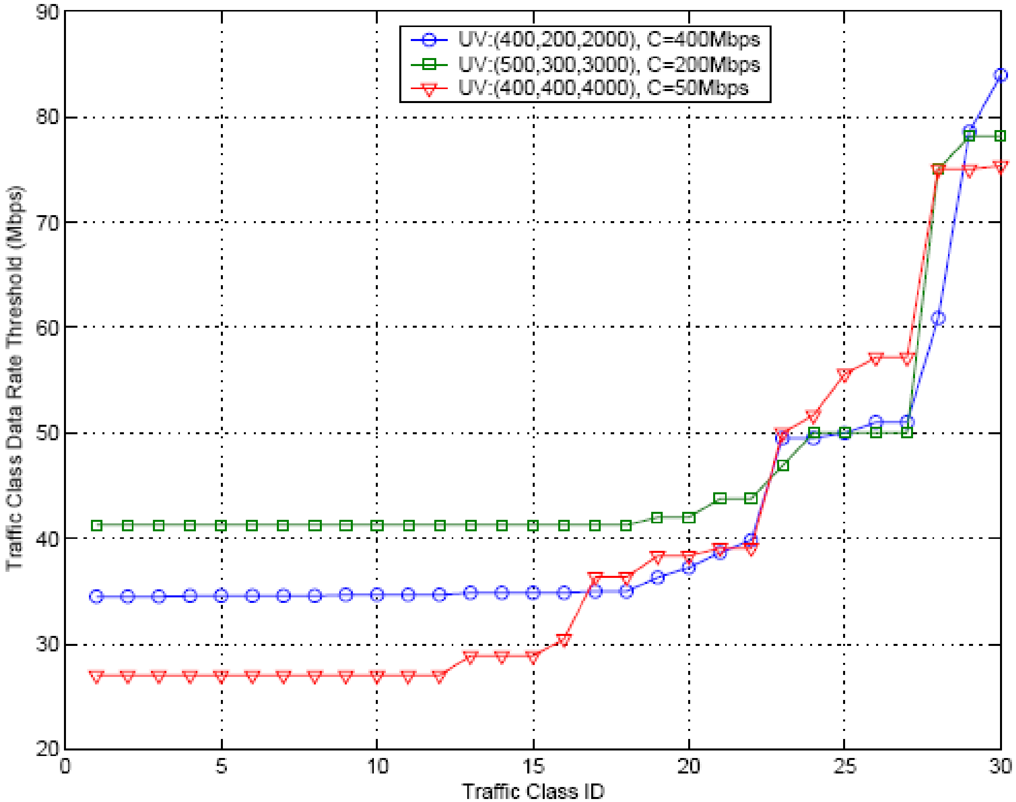


Figure 2. Admission thresholds for 25 nodes vs. flow class index, for the illustrative network when the UAV is placed at three different UAV locations

- When placed at low altitude (2000m), the UAV has high capacity (400 Mbps), its footprint span is limited, so that this location does not yield as good a performance as that obtained when placed at its optimal position.
- When placed at the higher (4000m) altitude, while yielding a wider footprint, and thus providing a direct UAV based route to each network flow class, its limited capacity resource level reduces its effectiveness.
- We note that the overall throughput levels attained when the UAV is placed at altitudes of 2km, 3km, 4km, are equal to 1250.3Mbps, 1392.1Mbps, 1165.3Mbps respectively.